Introduction

The field of soft robotics has seen important advancements in recent years, with soft robotic grippers emerging as a versatile solution for grasping objects with diverse shapes, sizes, and materials [1].

Soft grippers possess inherent compliance and adaptability that enables them to conform to the shape of the objects being grasped, allowing for a more secure and stable grip than traditional rigid actuators [2]. The performance of these grippers is largely influenced by their morphological and material properties, as well as the design and control strategies employed [3].

Understanding the physical principles and parameters underlying soft gripper performance can provide valuable insights that guide the optimisation of design and control strategies, leading to more effective, energy efficient, and flexible actuators [4].

This report aims to analyse a soft gripper's performance through image processing and analysis, exploring its potential to successfully grasp a custom-designed object with variable geometries and mass.

Following the completion of a series of experiments, the obtained results were analysed to evaluate the relationship between object shape, and the gripper's carrying capacity. In light of limitations of the experimental set-up and its influence on the results obtained, improvements to the experimental design, and proposals for future investigation into characterising and understanding soft actuator performance is discussed.

Design and Methods

Fabrication

Efforts were made to ensure that the gripper was fabricated to a high standard in the aim that results from subsequent tests would be reliable and representational of a well-made gripper.

Two-part EcoFlex 00-30 silicone elastomer was mixed in equal ratios and de-gassed by syringe de-pressurisation before filling the mould to the top. Gloves were worn at all times during fabrication to prevent skin borne contaminants from mixing into the elastomer. Whilst setting, the mould was placed on a horizontal surface (measured with a spirit level). The set elastomer was bound with a J-cloth such that the cloth's fibres extended along the width of the gripper when pressurised, for a stronger grip.

Experimental Design

Goals

Experimentation involved two sets of tests, aiming to understand specific characteristics of the soft gripper's performance. The first experiment sought to determine the relationship between the shape of the object to be gripped, the gripper's resulting shape, and the maximum mass that the gripper could carry. In the second set of tests, the goal was to identify the minimum amount of actuation pressure required by the gripper to grip and suspend an object for a given mass.

Procedure

Both experiments were run with the set-up shown in Figure 1. In both, a custom-designed test container seen in Figure 2 was placed on a support platform, upon which the gripper was placed. The gripper was then manually pressurised with a syringe to grip the container. A maximum of 30ml of air was used for pressurisation to reduce the risk of gripper bursting. The gripper was then tested in its ability to carry mass by lifting the syringe and pulling on the container.

The container was designed in Fusion360, and 3-D printed from PLA with an Ultimaker 2+. It features three top face diameters of 55mm ('small'), 60mm ('medium'), and 65mm ('large'). A cup-like shape enables mass control by adding and removing M6 nuts. Weighing was carried with kitchen scales accurate to 1 gram.

Design of the test container underwent several iterations, varying the curvature and diameters to provide a range of graspable surfaces, mimicking the gripper's shape when pressurised. To ensure that the central tracker of the gripper was not masked by the rim of the cup, a rib along the centre of the container was added. This was necessary because the central tracker tended to deflect downwards when engaged.

Quantifying Gripper Shape

The gripper's pressurised shape was quantified in Python [5]. By placing 7 landmarks symmetrically at key observed folding points on the gripper, detecting those landmarks with OpenCV, and skeletonising the gripper by linking them; the angle between each pair of adjacent links (pivot) could be used to characterise and quantify the gripper's shape, as seen in Figure 3.

Experiment 1

The first experiment was systematically conducted for each diameter of the test container. A test was defined as an attempt to assess whether the gripper could successfully suspend the container. To achieve this, the gripper was pressurized with 30ml of air, and the syringe was lifted. The test was deemed to pass if the gripper could suspend the container for 5 seconds.

For each diameter, 3 tests were performed at masses ranging from 18g to 65g. The mass was increased only if the gripper passed at least 2 out of 3 tests at the current mass. By contrast, if the gripper failed to pass the tests, the heaviest mass that the gripper successfully held for a given diameter was determined by the last passed test.

Experiment 2

The second experiment involved placing the gripper onto the test container, pressurizing it with 30ml of air and raising the container. Subsequently, air was gradually drawn into the syringe while monitoring the gripper's capacity to sustain the load. The syringe volume at which the gripper failed to carry the load was recorded. Relating this volume to pressure with theory would yield the required pressure for a given mass.

This procedure was conducted for each container shape, using the same set of masses employed in the first experiment. The process was repeated five times for each mass and each shape. The results were then averaged to obtain a representative value.

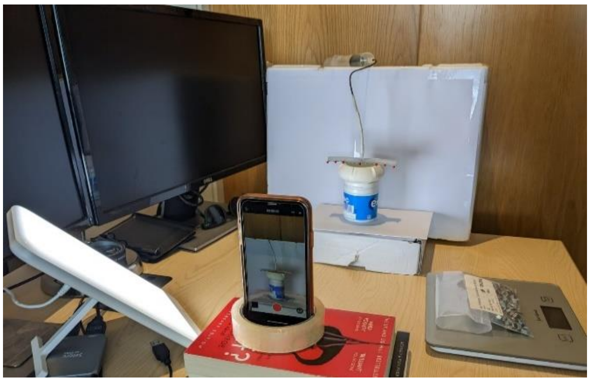

Figure 1 Experimental set-up

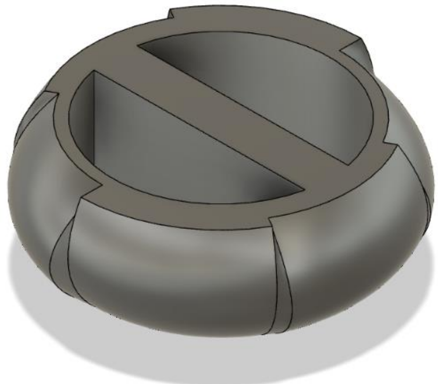

Figure 2 Test container

A

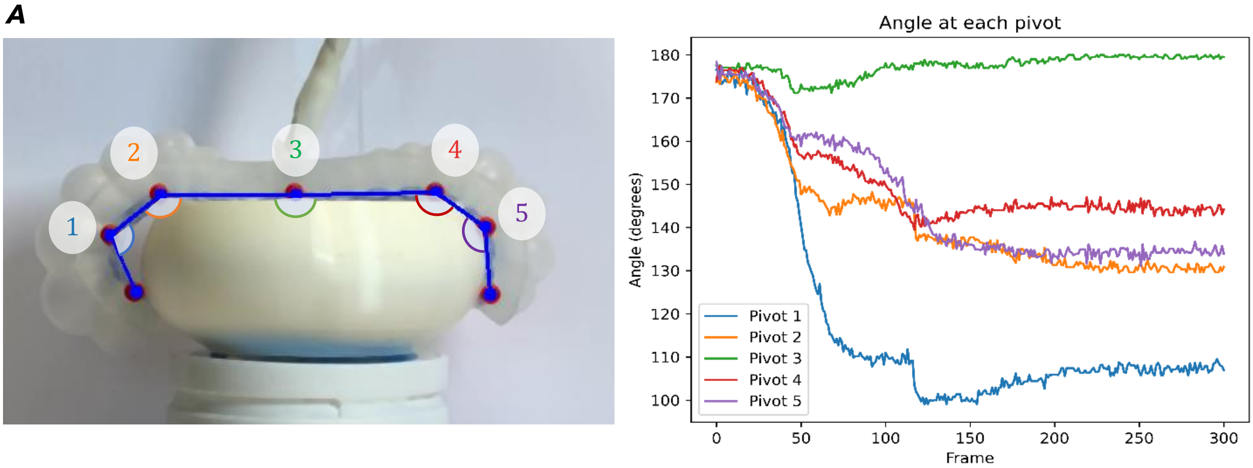

Figure 3
***A** Sample frame from recording 21 [5] processed post-experimentation with pivots labelled.*
***B** Corresponding frame-by-frame plot of angles between adjacent pivots.*

Results and Analysis

Experiment 1

In total, 45 tests were conducted as part of experiment 1, with each test capturing a recording that was analysed in Python. The full dataset is available at [5]. The small orientation was more successful in bearing mass and so had the most recordings with 18, followed by the medium orientation with 15, and the large orientation with 12.

The relationship between the container's orientation and the angle between pivots at maximum pressure is illustrated in Figure 4. The angle was derived by averaging the angle recorded on the frame prior to container movement, independent of the test passing or failing.

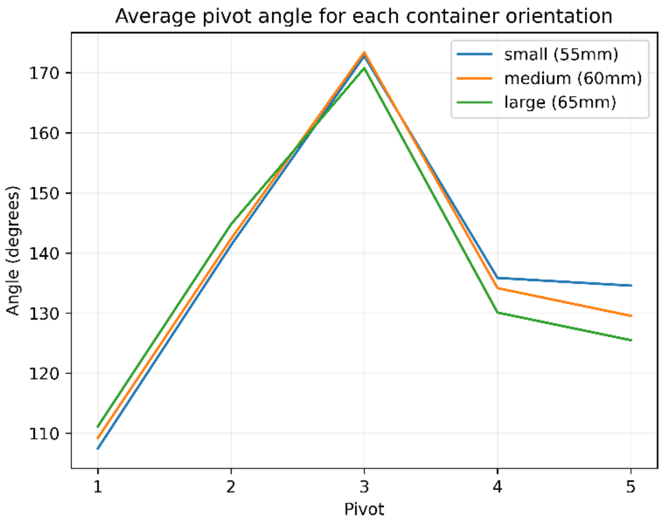

Figure 4. Angle at each pivot when gripper pressurised with 30ml. Averaged over all results for each container orientation.

Comparing the angles at Pivot 1 between different container orientations in Figure 4, it could be inferred that the morphology of the smaller orientation enables the gripper to form a more acute angle about the container at that point. At Pivot 1, the small orientation allowed an angle of 107.5 degrees on average, whilst medium and large enabled angles of 109.2 and 111.1 degrees respectively. Similarly, there was a difference in measured angles at Pivot 2 and Pivot 3, with averages and ranges of 143 and 3.5, and 172 degrees and 2.1 degrees, respectively.

At Pivots 4 and 5, the pattern of a smaller orientation leading to a more acute angle reverses. The angle between lines at Pivot 4 is 130.1 for the large orientation, but 135.8 for the small. This difference increases further at Pivot 5, with an angle of 125.5 for the large orientation, while the angle gets only slightly more acute for the small orientation to 134.6 degrees.

This change in behaviour is unexpected for two reasons. First, hypothesising that the soft gripper conforms to the container it is gripping, the small orientation should allow for more curling and more acute angles at all pivots. This is consistent with results depicted in Figure 4 for the first 3 pivots. Secondly, given the gripper and container are both designed to be symmetrical, different behaviour of the two sides is surprising, i.e., Figure 4 should be symmetrical.

A potential explanation for this difference is that as the gripper curls about Pivot 1, it pulls the gripper across the container so that its centre no longer aligns with the object centre, as shown in Figure 5. This causes the opposite Pivot 5 to drag up the side of the container, flattening it out. This action occurs because the left side (Pivot 1) inflates more quickly and more forcefully than the right side (Pivot 5), evidenced Figure 3B.

This phenomenon is especially pronounced for the small orientation as it is able to curl more about Pivot 1 earlier in pressurisation and drag the gripper further across the container. This effect was noted during experimentation – it was observed that Pivot 1's side of the gripper would pressurise earlier and with more force than Pivot 2. It is likely that this is the result of poor fabrication.

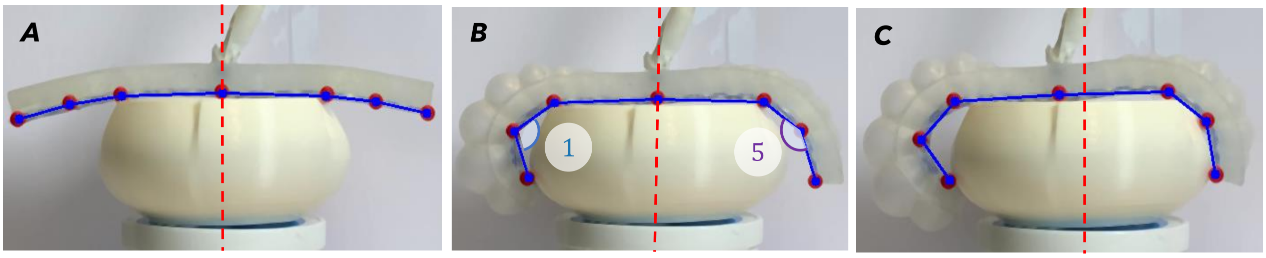

Figure 5. Frames 0, 100, and 125 from recording 21. As the gripper is pressurised, the actuator is dragged across to the left side of the container. Pivot 1 can become more acute than Pivot 5 as a result.
***A**: Pivot 1 angle = 176 degrees. Pivot 5 angle = 174 degrees*
***B**: Pivot 1 angle = 111 degrees. Pivot 5 angle = 155 degrees*
***C**: Pivot 1 angle = 99 degrees . Pivot 5 angle = 142 degrees*

Figure 6 displays a region of the mass vs angle plot, where each point represents the mean average angle obtained from all tests performed at that mass. The plot indicates that the maximum mass that the gripper can carry before failing is 63g for the small orientation, 60g for the medium orientation, and 49g for the large orientation. This finding supports the hypothesis that the smaller orientation of the test container would result in a greater capacity for carrying maximum mass.

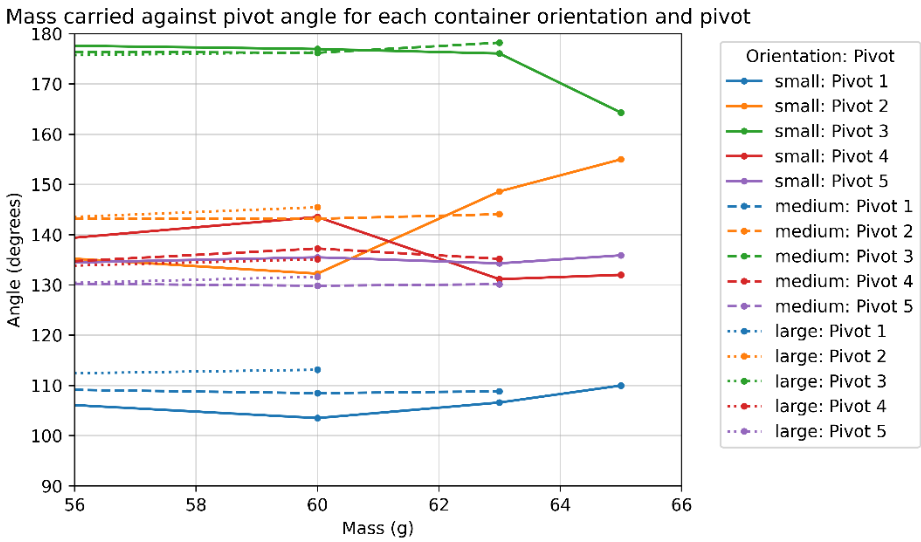

Figure 6 Region of interest of the carried mass vs. pivot angle plot

The region displayed in Figure 6 provides insight into the mechanism behind the gripper's reduced ability to bear greater masses. This effect is most apparent for the small orientation, shown by the solid lines in Figure 6. As mass is added to the test container, it gradually slides down the gripper, causing the gripper's limbs to be pushed outwards and the angles between Pivots 1, 2, 4, and 5 to increase.

This outward force continues to increase until a point is reached where the gripper can no longer maintain its grip on the test container, resulting in a failed test. In contrast to the behaviour of Pivots 4 and 5, Pivot 3 exhibits a distinct pattern whereby as more gripper moves towards the top of the container, the centre of the gripper rises with the pull of the syringe, and so pivot 3's angle becomes more acute.

Experiment 2

Despite precautions taken to mitigate the risk of gripper bursting, the full scope of experiment 2 could not be carried out due to gripper failure. The results consisted of a total of 8 tests, with 5 trials performed on the small orientation, 2 on the medium orientation, and 1 on the large orientation, after which the gripper burst. The number of tests conducted is insufficient to support a dependable or precise investigation, and therefore no data analysis was performed.

Discussion

In summary, the results support the hypothesis that a relatively smaller object is easier for the gripper to hold, allowing it to carry more mass. It is thought that this is a result of a smaller shape enabling the actuator to wrap around the object and support it from underneath. However, in this case, the tendency for one side of the gripper to inflate before the other produced questionable results, and led to the gripper's condition deteriorating over time, eventually bursting. This made it difficult to obtain controlled test results, and so necessitates a re-run of experiments with a more robust experimental set-up and a better-fabricated gripper.

The experimental set-up and computer vision analysis techniques used in this study have provided valuable insights into the behaviour of the soft gripper. However, their limitations suggest areas for improvement in future studies. For example, a removable platform and electrical pump would make tests more repeatable; higher fidelity masses and scales would provide a more accurate understanding of the force at which the actuator fails; and controlling camera-to-gripper perpendicularity and using non-invasive trackers would enhance accuracy and precision.

Further experimentation is required to answer the following questions: is there a limit to improvements in the gripper’s carrying capacity of smaller objects, to what extent does gripper symmetry affect performance, and what is the relationship between the energy required to pressurise the actuator and its maximum carry capacity for different shapes of objects? These experiments can inform designs through Real-Sim-Real exercises [4], improving actuator designs for specific use-cases.

Finally, the challenges associated with manufacturing soft-robotic grippers, and the irreplaceability and irreparability of failed soft actuators were brought to light through the processes of fabrication and experimentation. These challenges need to be addressed for future development of reliable soft actuators to support a growing adoption of soft-robotic technology in industry.

References

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